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A RAND NOTE

Attitude Orientation Control for a Spinning Satellite

Gerald Frost

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Prepared for the
United States Air Force

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PREFACE

This Note was prepared in response to a request by the Department of the Air Force, Headquarters Space Systems Division, to search for pertinent, pre-1960 RAND work pertaining to the "Williams patent." This Hughes Aircraft Company patent describes a method for attitude control of a spin-stabilized vehicle. The Note summarizes the contents of two internal RAND documents by the author on this method of attitude control.

SUMMARY

The Department of the Air Force, Headquarters Space Systems Division, and the National Aeronautics and Space Administration (NASA) are currently involved in litigation with Hughes Aircraft Company over the alleged infringement of the "Williams patent," which describes a method for attitude control of a spin-stabilized vehicle. This Note summarizes pre-1960 RAND work on this subject and presents informatin obtained from RAND personnel knowledgeable on this subject.

The Note also reviews the TIROS II magnetic torque attitude control method. The TIROS II meteorological satellite, launched on November 23, 1960, incorporated a magnetic actuation system for spin-axis orientation control. The activation system was ground-controlled to orient the satellite spin axis to obtain the desired pointing direction for optical and infrared sensor subsystems. The key findings of this study are as follows:

- There is no RAND documentation that directly parallels the "Williams patent" concept.
- Spin-axis attitude control for the low-earth-orbit (740-km altitude) TIROS II satellite was obtained by switching the current direction in a coil wrapped around the periphery of the satellite. The magnetic dipole moment due to the current coil acts as a bar magnet, which then interacts with the earth's magnetic field. The resulting torque causes the spin axis to precess. The current switching times, based on processing satellite orientation angles obtained from the on-board horizon and sun sensors, are commanded from the ground.
- The cold-gas-jet method associated with the "Williams patent" concept is pulsed at the appropriate time during each *spin* cycle. This differs from the magnetic torque method, where the spin axis can precess, assuming favorable geometry, as long as the current is on during the *orbit* cycle. The precessional direction is changed by switching the direction of current in the coil loop.
- The torque produced by magnetic induction is inadequate for changes in the spin-axis orientation of more than several degrees. Therefore, this method is not satisfactory for satellite mission concepts in which the spin axis must be continuously pointed at the earth during the orbit period.

- The applicability of the magnetic torque method significantly degrades as the orbit altitude is increased. At geosynchronous orbits, the earth's magnetic field intensity, and therefore the obtainable precessional rate, is reduced by a factor of more than 200 over the low-earth-orbit case.

CONTENTS

FIGURES

TABLES

I. INTRODUCTION

The "Williams patent" describes a method of attitude control for a spin-stabilized vehicle. This method is reviewed briefly below.

The "Williams patent" method for controlling the spin-axis orientation employs a reaction jet that applies a force to the satellite at a radial distance and parallel to the spin axis. The resulting torque produces a change in the orientation (or precession) of the vehicle spin axis. The reaction jet is pulsed at the appropriate time in the spin cycle. Ground-based control requires knowledge of the spin angle, which is obtained from measurements from satellite-mounted sun and earth sensors. These sensors provide the orientation of the spin axis and the spin-angle position of the reaction jet.

The "Williams patent" is based on the fundamental gyrodynamics law that relates spin angular momentum, applied torque, and vehicle precession, namely $T = \Omega \times H$, as shown in Fig. 1.

Using this description, we can break the control of the attitude of a spinning vehicle down into the elements shown in Fig. 2. For convenience, we have defined the following categories for reviewing pre-1960 RAND documentation pertaining to attitude control of a spinning vehicle:

- Spinning body dynamics
- Reaction control actuators
- Vehicle attitude sensors
- Orientation control logic

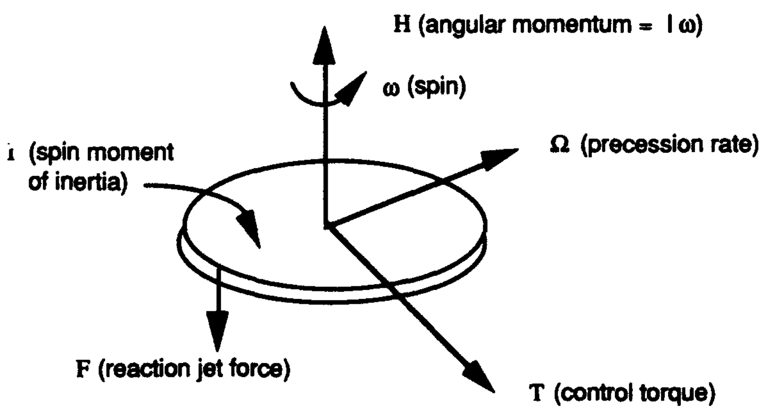

Fig. 1—Model of gyrodynamics

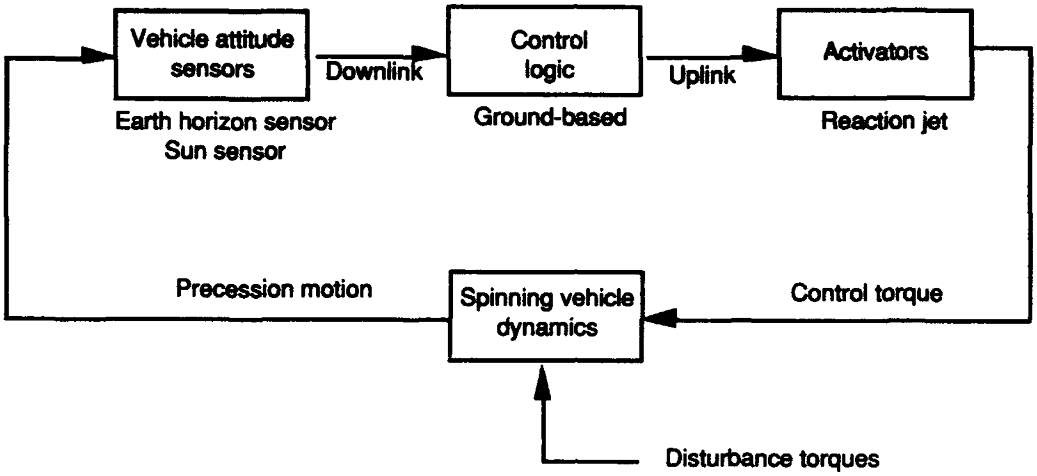

Fig. 2—Satellite attitude control scheme based on the "Williams patent"

II. RAND DOCUMENTATION ON SATELLITE ATTITUDE CONTROL

This section describes the information available at RAND on satellite attitude control.

UNCLASSIFIED REPORTS

The principal reference used to determine potentially relevant pre-1960 RAND documentation on attitude control of a spinning vehicle is the *Index of Selected Publications of The RAND Corporation, Vol. I, 1946-1962,* August 1962.

Subject categories and related documentation include:

- Aerodynamics and Fluid Mechanics: Stability and Control
  - — RM-1863-1, *An Analysis of the Rotational Motion of a Body During Reentry,* by T. Garber, January 25, 1957, revised June 28, 1961.
  - — P-1407, *On the Rotational Motion of a Body Reentering the Atmosphere,* by T. Garber, March 10, 1959.
- Applied Mechanics: Flight Celestial Mechanics
  - — P-1407, previously mentioned.
- Guidance and Control
  - — RM-2527, *General Equations of Motion of a Satellite in a Gravitational Gradient Field,* by T. Garber and R. Frick, December 9, 1959.
  - — P-1407, previously mentioned.
  - — P-1430, *Orientation and Control,* by T. Garber, February 24, 1958.
- Missiles, Ballistic
  - — RM-1863-1, previously mentioned.
- Space Flight

  Lunar
  - — RM-1730, *Lunar Instrument Carrier: Attitude Stabilization,* by R. Buchheim, June 4, 1956.
  - — RM-2183, *A Photographic System for Close-Up Lunar Exploration,* by M. Davies, May 23, 1958.
  - — P-1671, *Lunar Exploration by Photography from a Space Vehicle,* by M. Davies, March 5, 1959.

— P-2353-1, *Vehicle Dynamics: NSF/Stanford Rocket Propulsion Institute*, by R. Buchheim, July 5, 1961 (Note: Dated after 1960).

Miscellaneous

— RM-2113-1, *An Annotated Bibliography of RAND Space Flight Publications*, by R. Buchheim, February 10, 1958, revised March 1, 1959.

Orbits and Tracking

— P-2353-1, previously mentioned.

Satellites

— RM-1500, *Scientific Uses of an Artificial Satellite*, by H. Kallman and W. Kellogg, June 8, 1955.

— RM-2527, previously mentioned.

— P-2002, *Effect of Geometrical Libration on the Damped Motion of an Earth Satellite*, by L. Rowell and M. Smith, June 15, 1960.

— P-2353-1, previously mentioned.

Space Operations

— P-1430, previously mentioned.

MISCELLANEOUS SOURCES

Other sources of information include the following publications and consultations with current and former RAND researchers:

- Textbook
  - — *New Space Handbook*, by R. Buchheim, June 15, 1960, revised 1963.
- Classified Sources
  - — RM-1050, *Attitude Sensing and Control for a Satellite Vehicle* , by R. Roberson of North American Aviation, Inc., January 2, 1953 (Declassified; originally Confidential).
  - – Classified reports containing data on spin-orientation-angle control.
- Patents

  M. Davies of The RAND Corporation obtained a patent in August 1964 for a photographic apparatus for use on a spin-stabilized vehicle. The spin of the vehicle is utilized to scan the area to be photographed. To obtain unblurred

images, the film is driven at the vehicle spin rate, which is measured by photocells. However, the orientation of the spin axis is not changed.

- RAND Personnel

  Attitude control of a spin-stabilized vehicle was discussed with current RAND employees M. Davies, R. Frick, and T. Garber. In addition, we contacted the following former RAND employees knowledgeable on this subject : R. W. Buchheim, S. Greenfield, and W. Kellogg. Their phone numbers are available upon request.

SUMMARY

The unclassified RAND reports and attitude control subject categories are summarized in Table 1. We found no RAND publications that address all four categories. The most closely related report, P-1430, *Orientation and Control,* does not focus on precessional control. The author of report RM-1050, R. E. Roberson, was an expert on satellite attitude control employed by North American Aviation during 1953. This study treats the subject of satellite attitude control in detail but is not applicable to a spinning vehicle. At this time, no RAND documentation has been found that parallels the Williams scheme.

Table 1

PRE-1960 RAND DOCUMENTATION RELATING TO SPINNING VEHICLE ORIENTATION CONTROL

Document Number	Spinning body Dynamics	Torque Control Actuators	Vehicle attitude Sensors	Orientation Control Logic
RM-1863-1	Oscillatory motion of a body during atmospheric reentry	NA	NA	NA
P-1407	Equations-of-motion for body reentering atmosphere due to gravity and aerodynamic forces	NA	NA	NA
RM-2527	Dynamics of coupling between orbital and vehicle rotational motion	NA	NA	NA
P-1430	Discusses spin stabilization, Euler angles	Discusses torque control methods and disturbance	Includes self-contained reference systems and stellar aids	NA
RM-1730	Determines spin rate required for moon landing	Open- loop system, considers disturbance torques	NA	NA
RM-2183	Camera scan obtained by vehicle spin motion	Change spin rate by moving weights	Sun sensor for measuring vehicle spin rate	NA
P-1671	Camera scan obtained by vehicle spin motion	Change spin rate by moving weights	Sun sensor for measuring spin rate	NA
RM-1500	Establishes attitude requirements for various types of satellite experiments	NA	NA	NA
P-2002	Discusses closed loop attitude stabilization, not spin-stabilized	Reaction wheels and earth gravitational gradients	Horizon sensor	NA

NA = Not addressed

III. TIROS II SPIN-AXIS CONTROL METHOD

The TIROS I and II experimental meteorological satellites were orbited on April 1, 1960 and November 23, 1960, respectively (Refs. 1 through 4). TIROS I was developed originally under the sponsorship of ARPA and later under NASA, with technical direction provided by the U.S. Army Signal Research and Development Laboratory. TIROS II was developed under the sponsorship and technical direction of NASA. Both of these satellites were spin-stabilized for observing the earth's cloud cover with television cameras. A magnetic attitude control system for precession control of the vehicle spin axis was added to TIROS II after unexpected disturbance torques were observed on TIROS I. Vehicle sensors included a horizon detector to determine the spin-axis attitude and sun angle sensors, mounted around the periphery, to indicate the angle between the TV camera line of sight and the direction of the sun. The spin-axis orientation control was obtained by ground commands of steady currents in a coil wrapped around the periphery of the satellite. The current coil produces a magnetic dipole that interacts with the earth's magnetic field, causing a torque on the body. This torque precesses the spin axis to the desired orientation.

The magnetic torque method for spin-axis orientation control is reviewed below for both low earth and geosynchronous orbits. Results from this review are presented in the summary (pp. v–vi).

MAGNETIC FIELD SOURCE

The source of the earth's magnetic field can be represented by a magnetic dipole placed at the center of the earth of pole strength Q_m and length ℓ. An equivalent representation of that source is given by a closed circular loop of radius r_i through which the current I_e flows. These magnetic source models are described in Fig. 3. The magnetic dipole moment for the earth is given by

$$m_e = Q_m^+ \ell = I_e \pi r_i^2 .$$

The magnitude of the earth's magnetic dipole moment, obtained from Ref. 5, is equal to

$$m_e = 8 \times 10^{22} \qquad \text{amp-m}^2 .$$

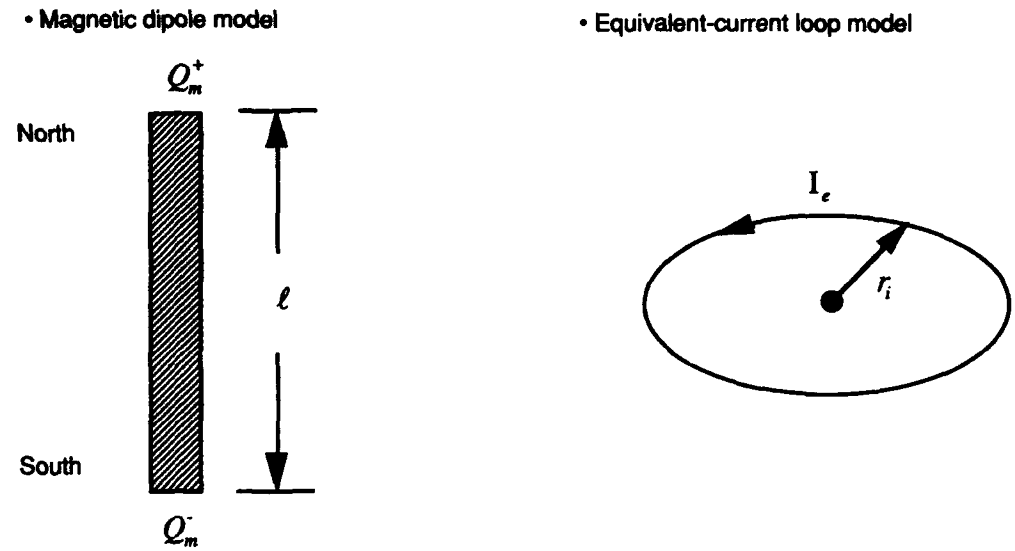

Fig. 3—Magnetic field source models

In terms of a current loop, the mean radius r_i of the earth's liquid core is approximately

$$r_i = 2.4 \times 10^6 \qquad \text{m},$$

which results in an equivalent current of

$$I_e = \frac{m_e}{\pi r_i^2} = 4.4 \times 10^9 \qquad \text{amp}.$$

The earth's magnetic poles are not aligned with the earth's geographic poles. The north magnetic pole is currently located near the Queen Elizabeth Islands in northern Canada, and the south magnetic pole is located in Antarctica, south of Australia, which corresponds to a misalignment of about 11.5 degrees from the earth's geographic poles. To simplify the model for magnetic induction, we assume that the magnetic dipole model is aligned along the earth's north geographic axis.

MAGNETIC FIELD STRENGTH

The magnetic dipole model representing the earth's field at point P is shown in Fig. 4.

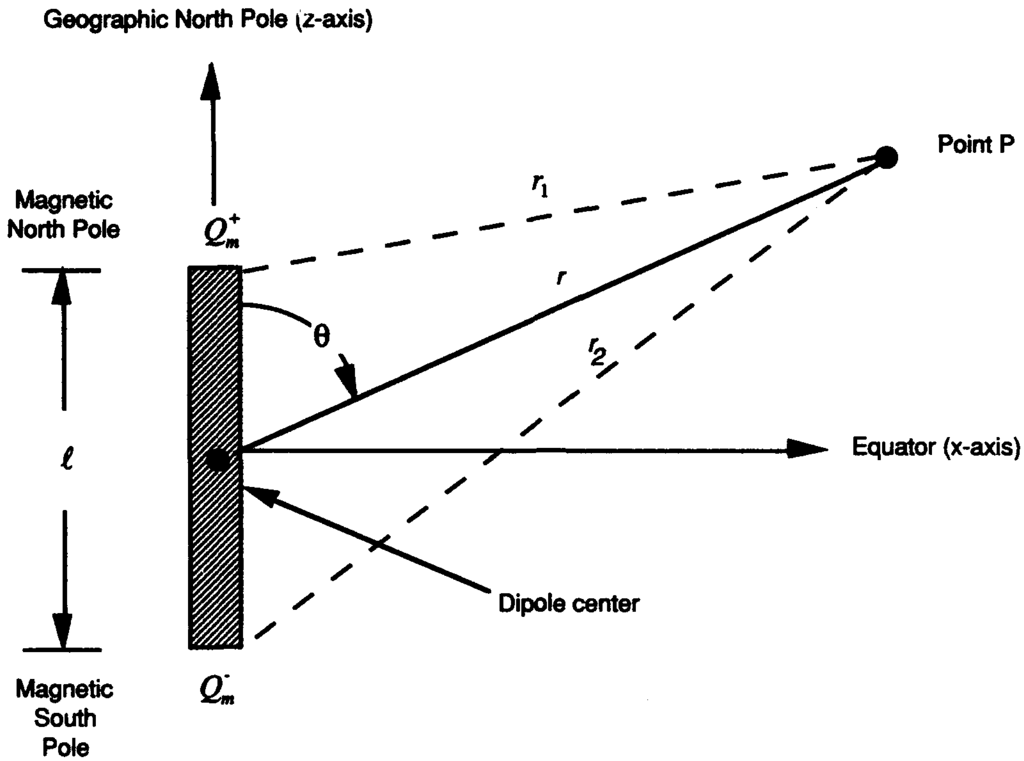

Fig. 4—Earth's magnetic dipole model

The approach in this model is to determine the magnetic field potential V_m at point P due to the magnetic dipole source. Based on experiments, the magnetic flux density **B** at distance r_1, due to Q_m^+, is known to follow the inverse square law, namely,

$$\mathbf{B} = \frac{\mathbf{F}}{Q_m^+} = \frac{\mu_0 Q_m^+}{4\pi r_1^2}\mathbf{a}_r \qquad \frac{\text{newton}}{\text{amp-m}} \text{ or } \frac{\text{weber}}{\text{m}^2}$$

where the unit vector $\mathbf{a}_r$ is along r_1. The permeability for free space is

$$\mu_o = 4\pi \times 10^{-7} \qquad \frac{\text{weber}}{\text{amp-m}}.$$

The gradient of the scalar magnetic potential is related to the magnetic flux density by

$$\mathbf{B} = -\nabla V_m ,$$

and therefore the scalar magnetic potential for a point P located at distance r_1 from pole Q_m^+, assuming $V_m(r_1 = \infty) = 0$, is

$$\mathbf{V}_m = \frac{\mu_o Q_m^+}{4\pi r_1} \qquad \frac{\text{newton}}{\text{amp}} .$$

For the dipole model of Fig. 4, the magnetic potential at point P is then

$$\mathbf{V}_m = \frac{\mu_o}{4\pi}\left[\frac{Q_m^+}{r_1} + \frac{Q_m^-}{r_2}\right] = \frac{\mu_o}{4\pi}\left[\frac{Q_m^+}{r_1} + \frac{Q_m^+}{r_2}\right]$$

For $r \gg \ell$,

$$r_1 \approx r - 0.5\ell\cos\theta$$
$$r_2 \approx r + 0.5\ell\cos\theta$$

Therefore,

$$V_m = \frac{\mu_o m_e}{4\pi r^2}\cos\theta$$

where the dipole magnetic moment is

$$m_e = Q_m^+\ell .$$

The next step is to determine the local earth vertical component (B_r), the horizontal component (B_θ), and the total (B_t) magnetic flux densities for the simplified, spherical earth-aligned dipole model of Fig. 5. Here, D is defined as the magnetic angle of inclination. Since $\mathbf{B} = -\nabla V_m$, the gradient in spherical coordinates is

$$\mathbf{B} = \frac{-\partial V_m}{\partial r}\mathbf{a}_r - \frac{1}{r}\frac{\partial V_m}{d\theta}\mathbf{a}_\theta$$

$$\mathbf{B} = \frac{\mu_o m_e}{4\pi r^3}\left[2\cos\theta\,\mathbf{a}_r + \sin\theta\,\mathbf{a}_\theta\right]$$

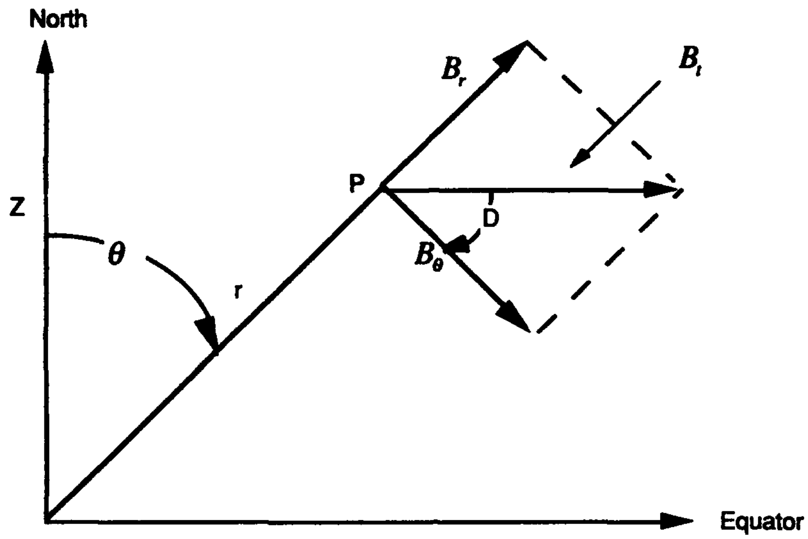

Fig. 5—Earth's magnetic flux components

and the magnitude of **B** is

$$|\mathbf{B}| = \frac{\mu_0 m_e}{4\pi\ r^3}\left[4\ \cos^2\ \theta + \sin^2\theta\right]^{\frac{1}{2}}$$

$$|\mathbf{B}| = \frac{\mu_0 m_e}{4\pi\ r^3}\left[1 + 3\ cos^2\ \theta\right]^{\frac{1}{2}}$$

The magnetic flux density **B** and magnetic field intensity **H** at the surface of the earth for

$$r = r_e = 6.37 \times 10^6 \text{ m}$$

are then

$$\mathbf{B} = 3.09 \times 10^{-5}\left[2\cos\theta\,\mathbf{a}_r + \sin\theta\,\mathbf{a}_\theta\right] \quad \text{weber/m}^2$$

and

$$\mathbf{H} = \frac{\mathbf{B}}{\mu_o} = 24.6\left[2\cos\theta\,\mathbf{a}_r + \sin\theta\,\mathbf{a}_\theta\right] \quad \text{amp/m}\ .$$

The magnetic angle of inclination is

$$D = \tan^{-1}[2/\tan\theta] \ .$$

Values for the vertical, horizontal, and total magnetic field intensity and angle of inclination as a function of latitude at the surface of the earth are given in Table 2.

Table 2
MAGNETIC FIELD INTENSITY AT EARTH'S SURFACE
(amp/m)

	Magnetic Latitude (deg)		
Parameter	0[a]	45	90
H_r (local vertical)	0	34.8	49.2
H_θ (local horizontal)	24.6	17.4	0
$\lvert H_t \rvert$ (magnitude)	24.6	38.9	49.2
D (deg)	0	63.4	90

NOTE: For conversion to CGS units,
- Magnetic field intensity H
  1 amp/m = $4\pi \times 10^{-3}$ oersted = 400π gammas.
- Magnetic flux density B
  1 weber/m^2 = 10^4 gauss

[a]Equator, $\theta = 90°$

At any radial distance greater than one earth radius, the magnetic field intensity is given by

$$\mathbf{H} = \frac{24.6}{(r/r_e)^3}\left[2\cos\theta\,\mathbf{a}_r + \sin\theta\,\mathbf{a}_\theta\right] \quad \frac{\text{amp}}{\text{m}} \ .$$

Field intensity is radial along the polar axis and is normal to the radial direction in the plane of the equator. Contours of constant magnetic field intensity in the plane of the equator are shown in Fig. 6.

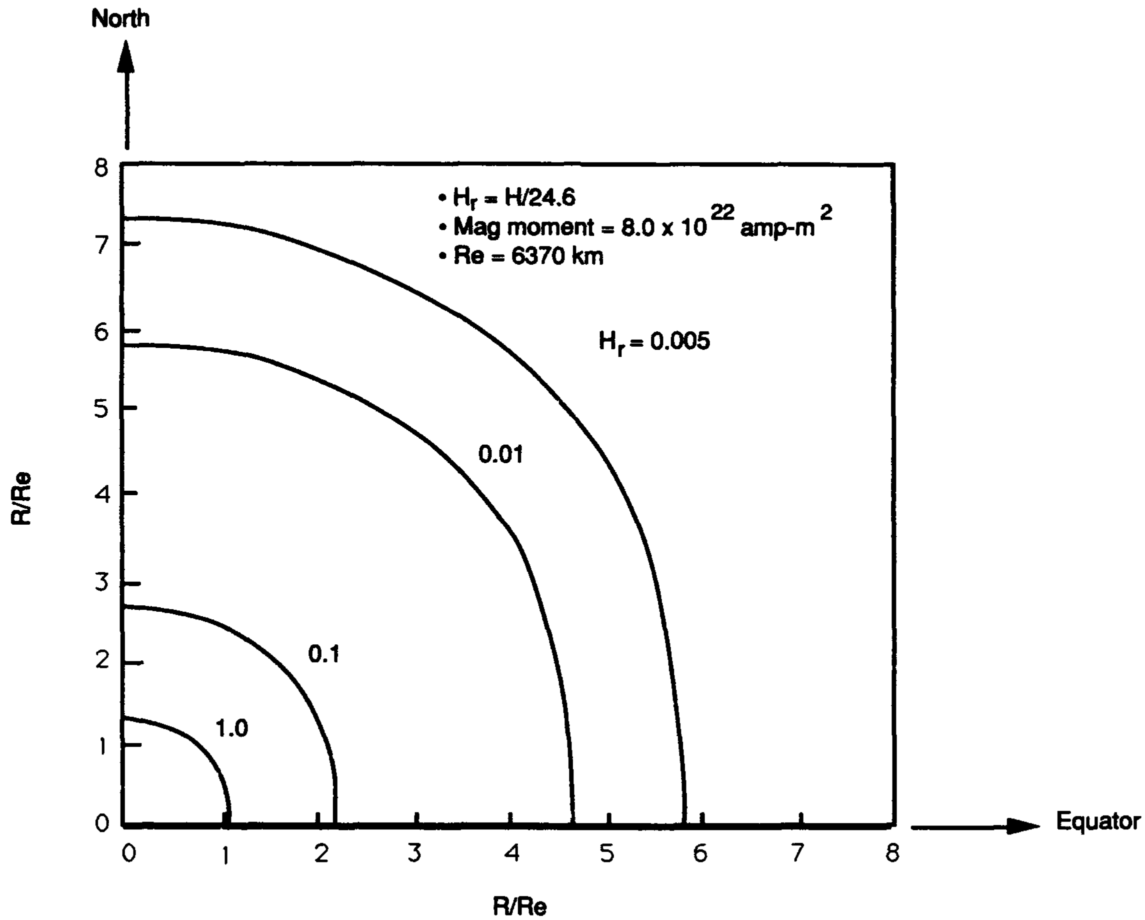

Fig. 6—Contours of constant magnetic field intensity

SATELLITE MAGNETIC DIPOLE MOMENT

The magnetic field of the earth can be utilized to control the orientation of the spin axis of a satellite. If a coil of wire is placed around the periphery of the spinning satellite, then the magnetic moment $\mathbf{m}_c$ of the coil is

$$\mathbf{m}_c = N\, I_c\, A_c\, \mathbf{a}_n$$

where

N = number of coil turns

I_c = current in coil loop (amps)

A_c = area of coil loop (m^2)

$\mathbf{a}_n$ = unit vector perpendicular to loop area, using the right-hand rule.

The torque on the current loop is then

$$\mathbf{T} = \mathbf{m}_c \times \mathbf{B} = \mu_o \mathbf{m}_c \times \mathbf{H}.$$

The precession rate Ω of the satellite spin axis is related to this torque and the spin angular momentum $\mathbf{H}_s$ by

$$\mathbf{T} = \Omega \times \mathbf{H}_s$$

The vector magnitudes and directions are shown in Fig. 7 for the case where the coil is wrapped around the periphery of the satellite such that the current dipole moment $\mathbf{m}_c$ is aligned with the spin angular momentum $\mathbf{H}_s$. To continuously point the spin axis at the earth's center requires 2-axis control, which would require two current coils mounted orthogonal to each other, as shown in Fig. 7.

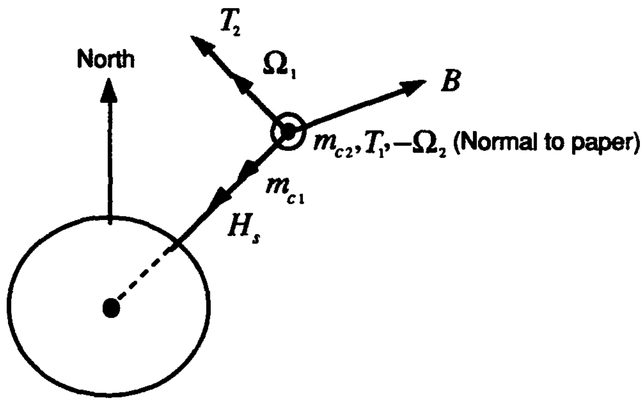

Fig. 7—Two-axis precession-rate control

TIROS II employed a one-axis control and therefore did not have this capability.

SATELLITE IN LOW EARTH ORBIT

For illustration, the magnitude of the spin-axis precession rate is calculated assuming one-axis control, TIROS II parameters, and an equatorial orbit. The actual precession rate for a satellite in an inclined orbit would be less, since the angle between $\mathbf{m}_c$ and $\mathbf{B}$ would vary sinusoidally over the orbit.

The magnitude of the spin-axis precession rate is calculated assuming the following parameters:

$$\mathbf{T} = \mathbf{m}_c \times \mathbf{B} = \mu_o \mathbf{m}_c \times \mathbf{H}$$
$$N = 200 \text{ coil turns}$$
$$I_c = 0.1 \text{ amps}$$
$$r_c = 0.4 \text{ m (coil radius)}$$
$$A_c = 0.5 \text{ m}^2$$
$$m_c = NI_cA_c = \text{amp-m}^2$$
$$r_s = 7120 \text{ km (750 km altitude orbit)}$$
$$\left(\frac{r_e}{r_s}\right)^3 = 0.716$$
$$H = 17.6 \text{ amp m}$$
$$\mu_o = 4\pi \times 10^{-7} \text{ weber/amp-m}$$
$$B = 2.21 \times 10^{-5} \text{ weber/m}^2$$
$$T = \mu_o m_c H = 2.21 \times 10^{-4} \text{ newton-m}$$
$$\text{k} = 0.3 \text{ m (radius of gyration)}$$
$$m_s = 100 \text{ kg (satellite mass)}$$
$$I_s = 9 \text{ kg-m}^2 \text{ (spin axis inertia)}$$
$$\omega_s = 1 \text{ rad/s (spin angular velocity)}$$
$$H_s = 9 \text{ kg-m}^2/s$$
$$\Omega = \frac{\mathbf{T}}{\mathbf{H}_s} = 2.4 \times 10^{-5} \text{ rad/s}$$

The orbit parameters for a satellite in circular orbit at h = 750 km altitude are

Gravitational parameter $K = 3.99 \times 10^5 \text{ km}^3/s^2$

Radius $r_e + h = 7120$ km

Velocity $v = \sqrt{\dfrac{K}{r_e + h}} = 7.49$ km/s

Angular rate $\omega_o = \dfrac{v}{r_e + h} = 1.052 \times 10^{-3}$ rad/s

Period $T = \dfrac{2\pi (r_e + h)^{3/2}}{\sqrt{K}} = \dfrac{2\pi}{\omega_o} = 5970\text{s}$ (99.5 min)

For one equatorial orbit, the satellite in this example can precess through an angle of

$$\phi = \int_{0}^{\frac{2\pi}{\omega_o}} \Omega \, dt = 0.14 \text{ radian } (8.2 \text{ deg})$$

Therefore, by controlling the currents in the coil, a magnetic dipole is formed which interacts with the earth's magnetic field and results in a torque acting on the coil loop, causing the spin axis to precess. For full two-axis control, two orthogonal current loops and favorable geometry are required.

SATELLITE IN GEOSYNCHRONOUS ORBIT

For a 24-hour circular orbit, the satellite is located at a radius of

$$r_g = \left[\frac{T\sqrt{K}}{2\pi}\right]^{\frac{2}{3}} = 42,270 \text{ km}.$$

At this radius the magnetic field intensity, and therefore the precessional torque, is *reduced* by a factor of

$$\left(\frac{r_g}{r_e + h}\right)^3 = (5.94)^3 \approx 210$$

compared with the low earth (h = 750 km) orbit. Therefore, this method of spin-axis attitude control is not very practical for other than low-earth-orbit satellites, for which control of the spin-axis orientation is limited to several degrees.

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